Numerical modelling of flow structures over transverse aeolian dunes

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Introduction

Numerical flow models have been widely applied in engineering disciplines for many years. In the last few years, there has been a proliferation of the use of Computational Fluid Dynamics (CFD) in the fields of geomorphology and hydrology (*see* Bates and Lane, 1998). These models enable an improved simulation of important processes providing prediction fields that allow considerable insight into the spatial distribution of these processes. CFD modelling has offered a new methodology that is complementary to traditional field and laboratory approaches. Indeed, the models can provide details of the flow field that are often difficult to measure and offer controlled conditions in which certain aspects of the experimental set up can be varied rapidly. This paper applies a CFD model to flow over transverse desert dunes and describes the sensitivity of different elements of the flow field to variations in geomorphic parameters. The model used is capable of simulating the highly turbulent reverse flow vortex in the lee of the dune and so is able to provide an acceptable solution of the downwind distance to flow re-attachment given variations in dune height, windward slope length and aspect ratio.

Methods

This paper employs the code PHOENICS^TM 3.4, which is one of several commercially available CFD programs. The hybrid-upwind scheme applied in the model is only first order accurate and can suffer from numerical diffusion when flow is highly skewed relative to the grid. Nevertheless, it is more stable than higher order schemes and investigations analogous to this present one have indicated that errors due to the interpolation scheme and not likely to be significant. In this study, the two-equation k-ε model, modified by renormalization group theory (Yakhot *et al*., 1992), is applied. This turbulence model is recommended for simulating flows with significant mean strain and shear. For example, it has been shown to perform better in the prediction of sheared and re-circulating flows over backward facing steps (*e.g.* Bradbrook *et al*., 1998).

In order to ascertain the capabilities of the model it was initially used to predict the measured flow velocities for the wind tunnel experiment of Walker and Nickling (in press). This successful validation procedure is described in more detail in Parsons *et al*. (2002). Based on this validation it was deemed appropriate to use the model to test the effect of simple dune geometry variations on certain elements of the flow field. The flow elements chosen for study were:

- Streamwise velocity at dune crest
- Streamwise velocity at dune toe
- Lee-side separation zone length

The latter of these parameters was of particular interest due to the ability of the model to predict reverse flow in the highly turbulent lee-side eddy. A Cartesian structured finite-volume approach was adopted and the dune geometry was represented in the model thorough a 'cut-cell' technique where the intersections of the geometry with the grid lines were determined and the areas and volumes of partially blocked cells were calculated to a high degree of accuracy. The equation formulation was modified to account for the local non-orthogonal intersection, resulting in significantly enhanced predictions. Model runs were undertaken with varying dune height, stoss slope length and dune aspect ratio.

Details of the differing dune geometries used in the model runs are shown in Table 1. All units are in centimetres and degrees (allowing testing against the wind tunnel data of Walker and Nickling, in press).

Table 1: Dune experimental details

Experiment Number	Lee base length	Stoss base length	Dune height	Aspect ratio	Lee slope angle	Stoss angle
1	12.80	56.00	8.00	0.143	32.0	8.13
2	12.80	112.00	8.00	0.071	32.0	4.09
3	12.80	28.00	8.00	0.286	32.0	15.95
4	12.80	84.00	8.00	0.095	32.0	5.44
5	12.80	42.00	8.00	0.190	32.0	10.78
6	6.40	56.00	4.00	0.071	32.0	4.09
7	25.61	56.00	16.00	0.286	32.0	15.95
8	9.60	56.00	6.00	0.107	32.0	6.12
9	19.20	56.00	12.00	0.214	32.0	12.10

Results

Data presented in Figure 1 confirm the view that an increase in dune height (*i.e.* an increase in aspect ratio) causes a corresponding increase in the length of the lee-side separation vortex (*i.e.* flow re-attachment occurs further downwind from the dune crest) (Walker & Nickling, 2002). The data also show, however, that a similar result occurs if dune height is maintained at a constant but stoss slope length is decreased (*i.e* an increase in aspect ratio). The different slopes of the lines in Figure 1 for changing stoss length and changing dune height indicate that the length of the separation zone is more sensitive to the latter. However, the fact that variations in these different elements of dune geomorphology produce differing results also indicates that the use of the aspect ratio to describe the structure of the lee-side airflow is flawed.
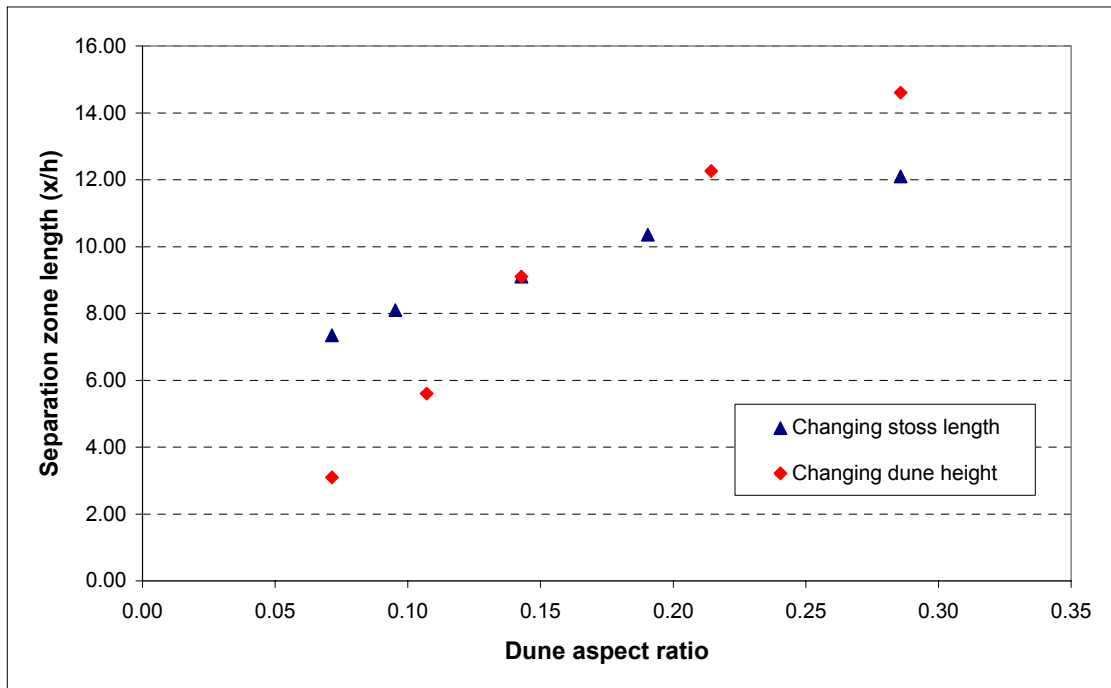
Figure 1: Variation of lee-side separation zone length with dune aspect ratio.
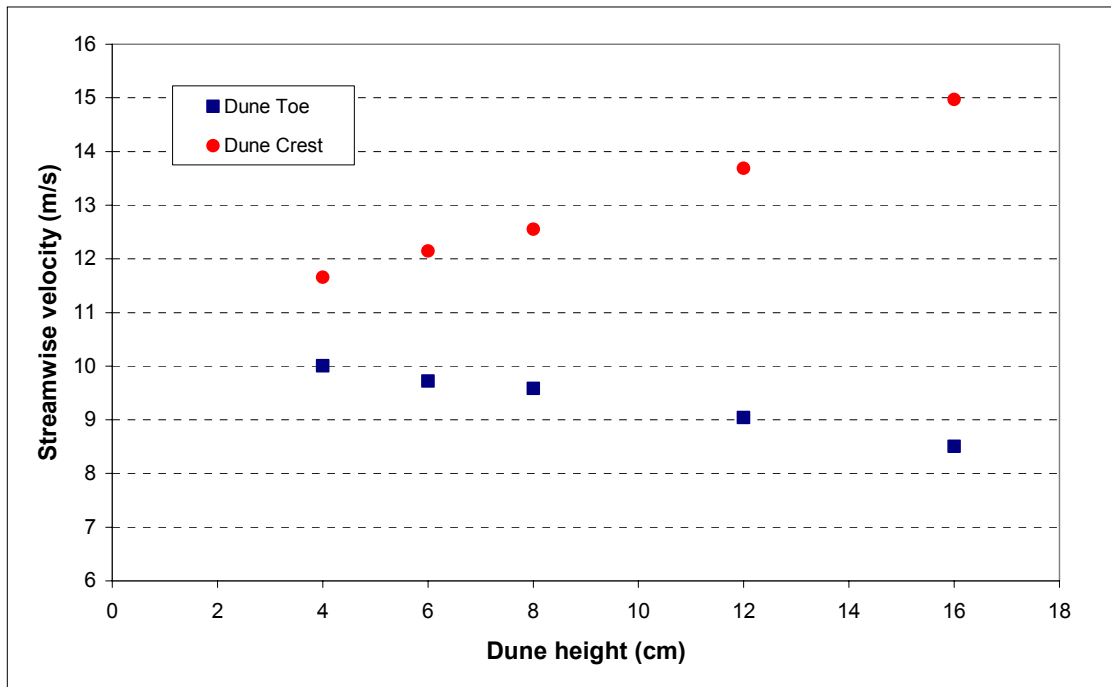
Figure 2: Streamwise velocity above the dune crest and toe with changing dune height.

Investigation of flow velocity at the dune crest and toe indicates that both acceleration at the crest and deceleration at the toe are sensitive to changes in dune height (Figure 2). Results not shown here show a similar but less intense relationship between flow velocity and dune stoss length at the toe, with increasing stoss slope length leading to an increase in velocity.

Both these results are expected given that stoss slope angle is more sensitive to a change in dune height than a change in stoss slope length. A steepening of this windward angle leads to both an increase in crestal acceleration and deceleration in velocity in the toe region (Wiggs *et al*. 1996).

Conclusion

Preliminary analysis of CFD-derived flow structures over a transverse desert dune has shown the potential to quickly test hypotheses relating to wind flow and dune geometry. The use of the aspect ratio to describe lee-side flow structures has been highlighted as an area of concern and the differing sensitivity of the flow to changing dune height and length has been described. Further detailed analyses of shear stress and turbulent momentum are planned as well as the incorporation of more realistic dune geometries consisting of concave-convex windward slopes.

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